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Remote Sensing Tools Assist in Environmental Forensics. Part I: Traditional Methods

George M. Brilis*†, Clare L. Gerlach‡§ and Robert J. van Waasbergen¶**

**U.S. Environmental Protection Agency, National Exposure Research Laboratory, P.O. Box 93478, Las Vegas, NV 89193-3478, U.S.A., ‡Lockheed Martin Corporation, 980 Kelly Johnson Drive, Las Vegas, NV 89119, U.S.A. and ¶Applied Environmental Data Services, 1411 Bluebonnet Trail, Arlington, TX 76013, U.S.A.*

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This is part one of a two-part discussion, in which we will provide an overview of the use of aerial photography, topographic mapping and photogrammetry in environmental enforcement actions. The visualization of spatial relationships of natural and man-made features can focus the scope of environmental investigation, and provide a simple, yet quantitative, historical record of changes in conditions on a site. Aerial photography has been used in environmental remote sensing since the early part of the 20th century. Aerial photos are valuable tools for environmental assessment because they provide objective, detailed documentation of surface conditions at a specific time. Furthermore, they can generally be obtained even in cases where access on the ground is denied to investigators. From aerial photos, precise quantitative information can be collected using photogrammetry. Such measurement and positional data can be produced in digital format for input into a Geographic Information System (GIS) for computerized analysis and display. Other information derived from aerial photographs requires specialized photointerpretive skills and experience. These include the recognition of vegetation mortality, oil-spill damage, and the ecological quality of water bodies. The location, extent and historical change of hazardous waste sites can be documented on topographic maps. These maps are often created from aerial photographs, and display the extent and location of real-world features by symbolizing them. The major advantage of maps over aerial photos is that maps can show things that are not visible from the air, while omitting unnecessary and distracting information. Because maps are derived products, they may contain bias in content and presentation, and they must be backed up by careful documentation and quality assurance protocols.

Keywords: remote sensing; photogrammetry; environmental enforcement; aerial photography; topographic mapping; environmental investigation.

Introduction

Various remote sensing activities, some of which are outlined below, have been used in military and civilian applications since the 1940s. In recent years, these reliable methods have been used by the U.S. Environmental Protection Agency (EPA) and other enforcement entities in the U.S. to locate, characterize, and define environmental features (Brewer, 1999). These features can include traditional areas of environmental concern such as hazardous waste sites and municipal landfills, or ecological features such as wildlife habitats, riverways and forests. In part one of this two-part series, we will provide an overview of aerial photography, topographic mapping and photogrammetry, and consider their use in environmental enforcement actions. In part two, we will report on the newer digital methods of remote sensing, geographic information systems and global positioning systems.

Table 1 shows a list of some interesting Web sites containing information about remote sensing mapping and photogrammetry.

† Author for correspondence. E-mail: george.brilis@epamail.epa.gov
§ E-mail: cgerlach@lmepo.com
** E-mail: robertvw@aeds.com

Spatial Aspects of Environmental Forensics

Visualizing spatial relationships between natural landforms, observed environmental or ecological damage, and documented human activities focuses the scope of investigations. The presentation of spatial documentation can be a simple, direct and persuasive way to identify or eliminate potentially responsible parties in enforcement action. Activities that can be documented to occur, or to historically have occurred, upstream from or adjacent to environmentally-damaged areas, can be catalogued and tracked. Spatial changes in the scope of the damages or threats can likewise be quantitatively documented. Remote sensing and spatial analysis can therefore be powerful tools in managing information in environmental damages assessment and enforcement.

Aerial Photography

Aerial photography is perhaps the oldest form of remote sensing. As early as 1858, photographs taken from hot-air balloons were used to map and plan the city of Paris (Estes, 1997). In 1862, balloons were used in the U.S. to map forests (not photographically) from the air. In 1906, G. R. Lawrence used a balloon-mounted camera to photograph the San Francisco earthquake and fire damage from an altitude of some

1527-5922/00/020063 + 05 $35.00/00

Table 1. Web sites to visit for further information on remote sensing, mapping and photogrammetry

United States Geological Survey (USGS) new page	http://www.usgs.gov/whats-new/whatsnew.html	While the information in this site does not reflect all the activities of the USGS, recent additions and changes to the public information provided on the Internet by USGS can be found on this page. New resources and interesting additions are made to the list as they are discovered
American Geophysical Union	http://earth.agu.org/revgeophys/bell02/bell01.html	Advances in aerogeophysics and precise positioning: gravity, topography, and high resolution applications
Australian Surveying and Land Information Group	http://www.auslig.gov.au/corpinfo/info/glossary.htm	Provides a glossary of terms and leads into Australia's National Mapping Agency
National Aerial Resources	http://www.nar.com	This private company provides custom aerial photography and forensic services including research and acquisition of aerial photography, photo interpretation and litigation support services
U.S. Environmental Protection Agency, National Exposure Research Laboratory, Environmental Sciences Division	http://www.epa.gov/crdlvweb/tsc/remote-sen.htm	Lists the Remote Sensing Technologies Index of capabilities of the indicated division

600 m, arguably the first environmental use of aerial photography. Aerial photos are powerful tools for environmental assessment, because they provide an unbiased, detailed view of the situation at a specific time. A specially calibrated aerial camera is used to ensure accurate photography for later use in the map production process (Moss, 1999).

Aerial photography is of particular value in situations where uncooperative owners deny intrusive sampling or observations. A landmark case involving aerial photography is *Dow Chemical Co. v. United States*. The following direct excerpt from the U.S. Supreme Court decision provides an example of an environmental forensic case and demonstrates that no permission is needed for a fly-over when a federal authority is conducting an investigation:

> Petitioner Dow Chemical Co. operates a 2000-acre facility manufacturing chemicals at Midland, Michigan. The facility consists of numerous covered buildings, with manufacturing equipment and piping conduits located between the various buildings exposed to visual observation from the air. At all times, Dow has maintained elaborate security around the perimeter of the complex barring ground-level public views of these areas. It also investigates any low-level flights by aircraft over the facility. Dow has not undertaken, however, to conceal all manufacturing equipment within the complex from aerial views. Dow maintains that the cost of covering its exposed equipment would be prohibitive.
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> In early 1978, enforcement officials of EPA, with Dow's consent, made an on-site inspection of two power plants in this complex. A subsequent EPA request for a second inspection, however, was denied, and EPA did not thereafter seek an administrative search warrant. Instead, EPA employed a commercial aerial photographer, using a standard floor-mounted, precision aerial mapping camera, to take photographs of the facility from altitudes of 12,000, 3000 and 1200 feet. At all times the aircraft was lawfully within navigable airspace. See 49 U.S.C. App. 1304; 14 CFR 91.79 (1985). [476 U.S. 227,230]
>
> EPA did not inform Dow of this aerial photography, but when Dow became aware of it, Dow brought suit in the District Court alleging that EPA's action violated the Fourth Amendment and was beyond EPA's statutory investigative authority. The District Court granted Dow's motion for summary judgment on the ground that EPA had no authority to take aerial photographs and that doing so was a search violating the Fourth Amendment. EPA was permanently enjoined from taking aerial photographs of Dow's premises and from disseminating, releasing, or copying the photographs already taken. 536 F. Supp. 1355 (ED Mich. 1982).
>
> The District Court accepted the parties' concession that EPA's "quest for evidence" was a "search", Id., at 1358, and limited its analysis to whether the search was unreasonable under *Katz v. United States*, 389 U.S. 347 (1967). Proceeding on the assumption that a search in Fourth Amendment terms had been conducted, the court found that Dow manifested an expectation of privacy in its exposed plant areas because it intentionally surrounded them with buildings and other enclosures. 536 F. Supp., at 1364–1366.
>
> The District Court held that this expectation of privacy was reasonable, as reflected in part by trade secret protections restricting Dow's commercial competitors from aerial photography of these exposed areas. Id., at 1366–1369. The court emphasized that the use of "the finest precision aerial camera available" permitted EPA to capture on film "a great deal more than the human eye could ever see". Id., at 1367.
>
> The Court of Appeals reversed. 749 F.2d 307 (CA6 1984). It recognized that Dow indeed had a subjective expectation of privacy in certain areas from ground-level intrusions, but the court was not persuaded that Dow had a subjective expectation of being free from aerial surveillance since Dow had taken no precautions against such observation, in contrast to its elaborate ground-level precautions. Id., at 313. The court rejected the argument that it was not feasible to shield any of the critical parts of the exposed plant areas from aerial surveys. Id., at 312–313. The Court of Appeals [476 U.S. 227, 231], however, did not explicitly reject the District Court's factual finding as to Dow's subjective expectations.
>
> Accepting the District Court finding of Dow's privacy expectation, the Court of Appeals held that it was not a reasonable expectation "[w]hen the entity observed is a multi-building complex, and the area observed is the outside of these buildings and the spaces in between the buildings". Id., at 313. Viewing Dow's facility to be more like the "open field" in *Oliver v. United States*, 466 U.S. 170 (1984), than a home or an office, it held that

> the common-law curtilage doctrine did not apply to a large industrial complex of closed buildings connected by pipes, conduits, and other exposed manufacturing equipment. 749 F.2d, at 313–314. The Court of Appeals looked to "the peculiarly strong concepts of intimacy, personal autonomy and privacy associated with the home" as the basis for the curtilage protection. Id., at 314. The court did not view the use of sophisticated photographic equipment by EPA as controlling.
>
> The Court of Appeals then held that EPA clearly acted within its statutory powers even absent express authorization for aerial surveillance, concluding that the delegation of general investigative authority to EPA, similar to that of other law enforcement agencies, was sufficient to support the use of aerial photography. Id., at 315. (United States Supreme Court\7476 U.S 227)

The aerial photographic holdings in the EPA and other agencies of the federal government are a wealth of spatial and temporal data about environmental conditions and processes. The EPA National Exposure Research Laboratory in Las Vegas, Nevada (NERL-LV), currently provides qualitative information that is interpreted from aerial photographs to characterize hazardous waste sites, analyse wetlands, identify ecological resources and to meet a number of environmental monitoring needs, and has the capability to supply highly accurate quantitative information for similar applications.

Technique

Photographs can be taken from aeroplanes and satellites. In general, the altitude at which the photo is taken, and the capabilities of the equipment, determine the level of detail (resolution) that can be seen. In selecting an altitude for the fly-over, there is a trade-off between resolution, coverage, and horizontal distortion: photos taken from a lower altitude can capture more detail, but will cover a smaller area and will suffer more horizontal distortion toward the edges.

Once photographs are taken, they may be used to collect precise quantitative information using a process called photogrammetry. Photogrammetric data were traditionally produced from aerial photographs using very precise photo-measurement devices called analytical stereoplotters. More recently, computerized systems have made it possible to generate, reproduce, and transmit data more quickly. Photogrammetric devices, typically calibrated to the micron level, enable the scientist to create complex mathematical models that correct for known distortions in the photographs. From these three-dimensional photo models, highly accurate measurements and positional data can be derived for mapping and analytical purposes. These data can be produced in digital format directly for input into a Geographic Information System (GIS) for computerized handling, display, and analysis of spatial information. Most areas in the United States are regularly (some annually, other perhaps once every five to ten years) photographed from the air by agencies such as the United States Geological Survey. These "general purpose" air photos typically provide horizontal resolutions of 2.85 to 10 feet. Air photo missions flown for specific projects (covering a lesser area) can often provide resolutions of 0.85 feet or better.

Thematic map products

Cartographic information can be produced from aerial photographs to meet National Map Accuracy Standards (U.S. Geological Survey, 1997). The information can be traditional map features such as roads and hydrology or special map layers such as historical hazardous waste site activity and fractures in the bedrock. Any information that can be derived from the aerial photo can be accurately mapped in a digital format. Once the photo model is established, thematic information represented by points, lines, and polygons can be input directly in digital format without transfer to a hard-copy map and digitizing from the map base (Husack *et al*. 1999). This saves time and reduces errors.

Some information produced from aerial photographs and used to create thematic maps or photo overlays requires expert interpretation. The recognition of changes in appearance of vegetation, occurrence of man-made structures and evidence of environmental damage, such as oil-spills, requires specialized photo-interpretation skill and experience. Aerial photography may also be obtained with specialized photographic film that is sensitive to nonvisible light such as infrared light. Photographs sensitive to near infrared radiation are used to detect and characterize thematic information such as vegetation type and stress, land/water boundaries, the ecological quality of water bodies (e.g. presence of algal blooms), and other features of environmental significance.

Mensuration products

Exact measurements can be accomplished on an analytical stereoplotter or in soft-copy electronic format to help characterize activity of environmental interest. For example, in studying hazardous waste sites, the volume of waste accumulation and changes in this volume are needed to evaluate remedial options. Also, precise distance and area measurements can be utilized for risk assessment and other site characterization activities.

Precise location of features

Any feature that is observable on an aerial photograph can be accurately referenced to a coordinate system. Photogrammetry can be extremely useful for collecting and recording the coordinate data that are required by the EPA Locational Data Policy. Information that is not readily visible on photographs, such as property boundaries or pipelines locations, can be superimposed digitally onto the photo model for special mapping or interpretive purposes.

Cartographic information that depicts the elevation of the land surface, such as the contour map or the digital elevation model, can be produced by photogrammetric techniques. The resolution of this data can be tailored to the specific needs of the project.

Advantages

Photogrammetric products generated from current and historical photos have the same advantages as data that are interpreted from aerial photos: they form a permanent record of present and past conditions, they are defensible in court, and they serve as valuable aids to site-specific field work. Furthermore, photogrammetric data are largely non-interpretive. The ability to provide quantitative measurements as a supplement to qualitative photointerpretation products will significantly enhance the products and services available to the forensic community.

Topographic Mapping

The location, extent, and historical change in the nature of hazardous waste sites is of great importance to the EPA, and these features can be documented through the creation of topographic maps. Topographic (elevation) maps are simple, effective, and graphic tools for recording the elevation of the terrain and quantifying selected characteristics of hazardous waste sites. These maps are most often created from aerial photographs and, since national archives of coverage date back more than 50 years, maps can be created that reflect historical site conditions.

Topographic maps provide a quantitative, yet easy-to-use way to understand spatial relationships between landforms, elevations, and features at hazardous waste sites. Topographic maps (which may show, in addition to site elevation differences, planimetric information such as buildings and roads) display the extent and accurate geographic location of real-world features by symbolizing them, and by removing unnecessary and distracting information. This is the major advantage that maps have over aerial photographs, which show everything that is visible from the air and nothing that is not. Because a topographic (and thematic) map is an interpreted simplification of the real world, care must be taken to prevent bias in content and presentation. In order for topographic and thematic maps to be useable in a legal setting, they must be backed up by careful documentation and quality assurance protocols.

Technique

A typical topographic mapping project includes planning, a cost estimate, arrangement for necessary geodetic surveys, aerial photographic over-flights, and map production. Most small and medium scale maps are made from aerial photographs, and photogrammetric sciences are a fundamental part of modern map making. Topographic base maps can be produced from aerial photographs using special instruments that create a model of the terrain to produce a contour map. By using two or more slightly offset photographs over the same area (stereo-pairs), changes in elevation can be accurately measured and recorded. The base map may be generated as hard-copy, or in digital form for later use with GIS. The same aerial photographs can be interpreted to assess the environmental remediation actions at a site.

Scope

In addition to basic positional information about ground elevation and locations of objects, maps can serve as the base for a targeted sampling grid, or for recording specialized information such as land disposal activity, population distribution, geologic fractures, vegetation communities, wetland delineation, and land use. When compared with historical aerial photographs or maps, these maps can provide both qualitative and quantitative information on changes in volume and elevation (e.g. last year there was a mound three times larger than the present one; or, between 1998 and 2000, there were 100,000 cubic yards of material placed in the landfill). Topographic information may be entered into a GIS for future referral. The information on these maps can provide answers to critical environmental questions such as the probable sources of contamination and the transport and fate of those contaminants.

Advantages and limitations

Topographic mapping is a mature technology that is evolving to meet the needs of the environmental community. Advances in computer technology and optical sciences continue to improve topographic mapping capabilities. Table 2 shows some advantages and limitations of topographic mapping.

Table 2. Some attributes to consider when choosing topographic mapping for environmental assessment

Advantages	Limitations
Legally defensible data	Seasonal and weather restrictions
Permanent historical record	Complexity of technology
Digital or analog format	Generalizes extent of ephemeral features
Geographic relationships are symbolized and clearly demonstrated	Interpretive
Quantitative measurements can be made	

Remote Sensing in Environmental Enforcement Actions

Remote sensing, topographic and thematic mapping and photogrammetry can support environmental enforcement actions. The following are some of the procedures observed in supporting environmental enforcement actions using remote sensing and mapping tools.

(1) Acquisition, indexing and archiving of imagery, topographic maps and all photo-derived documents.
(2) Chain-of-custody documentation of imagery, which records the handling of the imagery from supplier, through shipper and in-house handling, to customer receipt.
(3) Certification of authenticity of imagery and product documents used in courtroom testimony.
(4) Depositions or affidavits by expert witnesses, trained and experienced in environmental disciplines.

Remote sensing and mapping as used within the EPA has supported general counsels of various EPA Regions, United States Department of Justice attorneys, and state attorneys general offices. Specific cases have involved prosecutions brought under Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), Resource Conservation and Recovery Act (RCRA), Clean Water Act, and National Environmental Policy Act. In the instances where the actions culminated in outcomes favorable to the EPA, the penalties have included cost recoveries in civil proceedings, corporate fines, and fines and prison sentences to individuals involved in criminal proceedings.

Future Plans

Remote sensing and mapping technologies continue to develop for practical environmental usage. The basic topographic mapping process is being augmented by a series of related monitoring techniques that will provide new thematic mapping products. Among these are: increased reliance on digital methods; the use of orthophotography (hard-copy imagery corrected to map-quality standards); land use/land cover mapping from satellite data; the use of nonvisible spectral bands and RADAR imagery; and the development of various digital products in a GIS format. More of the basic photogrammetry and photointerpretation products will become available in digital, GIS formats.

In part two of this series, we will explore the advantages of digital remote sensing technologies such as geographic information systems and global positioning systems.

References

Brewer, C.A., Ed. 1999. Special Issue: The State of U.S. Cartography. *Cartog. Geograph. Info.* **26**.

Estes, J.E. 1997. The Remote Sensing Core Curriculum. On-line course, University of California at Santa Barbara, http://grouchy.geog.ucsb.edu/rscc/vol1/lec1/1lecture.html.

Husak, G.J., Hadley, B.C. and McGwire, K.C. 1999. Landsat thematic mapper registration accuracy and its effects on the IGBP validation. *Photogramm. Eng. Rem. S.* **65**, 1033–1039.

Moss, L. 1999. Match map scale to fit your needs. *Imaging Notes* **14**, 10.

United States Geological Survey. 1997. *National Map Accuracy Standards*, http://mapping.usgs.gov/mac/isb/pubs/factsheets/fs07896.html.

Notice

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